WESE Workshop
Turbine Level Integrated Design Approaches
Hub Height Example

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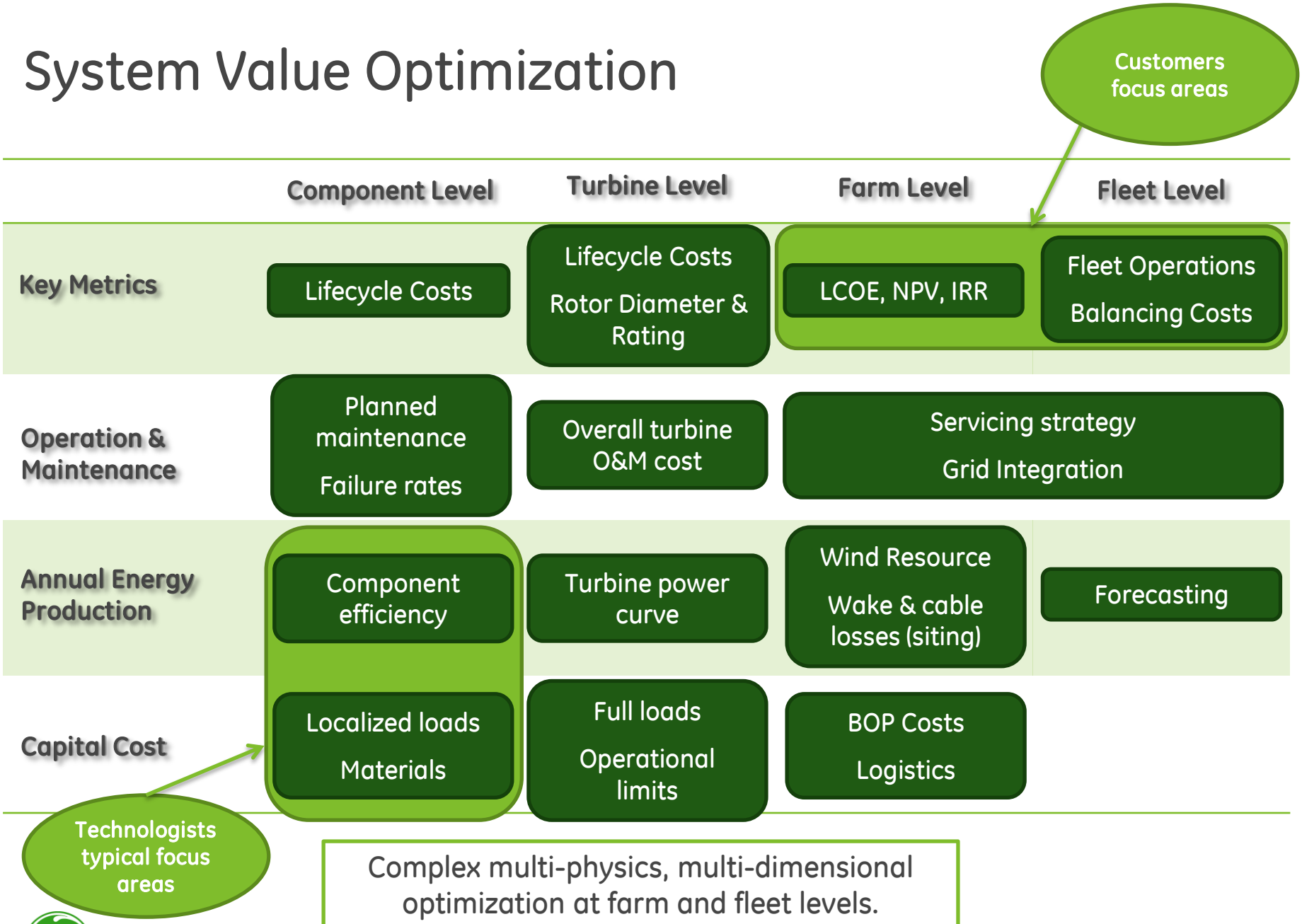
January 15, 2014

Imagination at work.

System Value Optimization



Complex multi-physics, multi-dimensional optimization at farm and fleet levels.

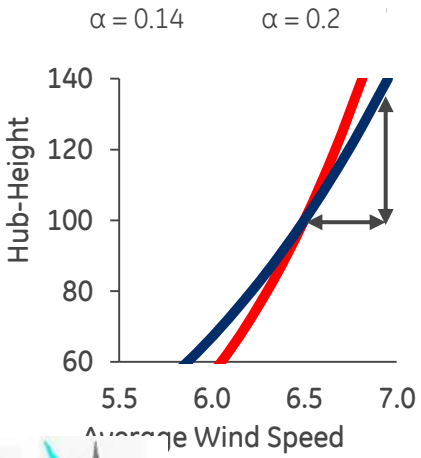
Hub Height Optimization – Component Level

Energy of Taller Hub Heights

- Higher mean *wind speed*

$V_h = V_{ref} (h/h_{ref})^{\alpha}$

  - h is the height above ground
  - α is the wind shear coefficient
  - Typically $0.14 \leq \alpha \leq 0.20$ (Depends on terrain)



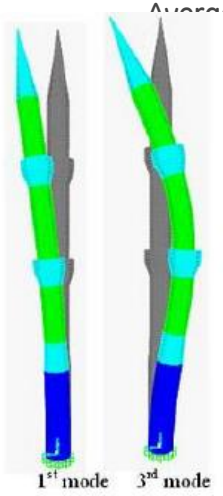
Hub-Height	δAEP 0.14	δAEP 0.2
80	-9%	-13%
100	0%	0%
120	8%	12%
140	15%	22%

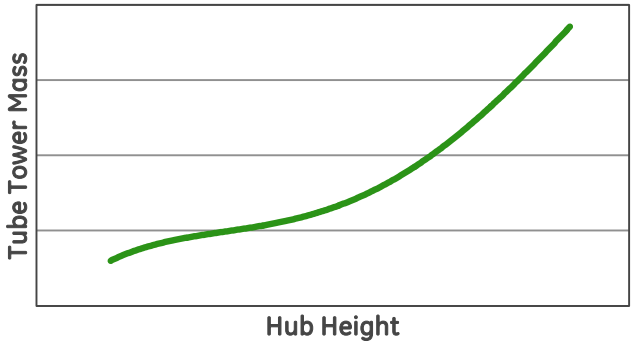
Costs of Taller Hub Heights

- Non-linear increasing *cost of tower*

Above ~100m hub height, tower natural frequency becomes the governing design factor

Shipping dimensional limit of 4.5m diameter





Optimization based on lowest tower cost / AEP

Hub Height Optimization – Turbine Level

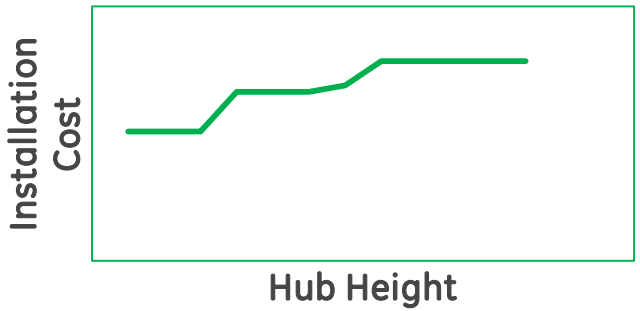
Energy of Taller Hub Heights

- Higher mean *wind speed*
- Reduced *wind shear*
- Reduced *turbulence*

} Potential impact to loads and structures design

Costs of Taller Hub Height

- Non-linear increasing *cost of tower*
- *Logistic* costs & constraints
- *Installation* costs
- Increase in *O&M* costs



Installation Costs

Tower logistic costs

Optimization based on lowest turbine cost / AEP

Hub Height Optimization – Plant Level

Energy of Taller Hub Heights

- Higher mean *wind speed*
- Reduced *wind shear*
- Reduced *turbulence*
- Value depends on *market pricing*
- *Wake & cable losses*
- Increased *rotor diameter & rating*

Costs of Taller Hub Height

- Non-linear increasing *cost of tower*
- *Logistic* costs & constraints
- *Installation* costs
- Increase in *O&M* costs
- *BOP* costs
- *Economies of scale*

Optimization based on Customer Metric

North American Optimized Product

Large Project Sizes (often >50 turbines)

Competes with variable cost of gas … low PPA values

Moderate wind resource … IEC Class II & III

Manage cost & performance for low PPA's … lower hub heights

European Optimized Product

Constrained by land available … Small farm sizes

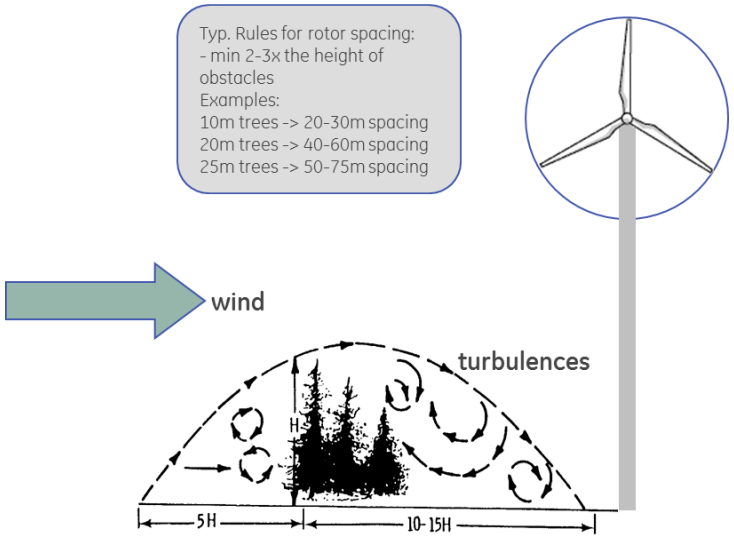
Strong feed-in tariff rates … AEP valued

Poorer wind resource … IEC Class III & IV

Increasing size can pay off with high feed-in tariffs … higher hub heights

Where Would We Expect Tall Towers

Impact of forested terrain



Key issue in Finland, Sweden and Germany

Impact of forested terrain …

- high turbulence above tree line … negative impact on site suitability / turbine life
- Boundary layer above trees resulting in very high shear

Economic value drivers

PPA 0.06	6.0 m/s	7.0 m/s
0.2 shear	82	86
0.3 shear	262	264
0.4 shear	444	441

PPA 0.08	6.0 m/s	7.0 m/s
0.2 shear	201	206
0.3 shear	442	444
0.4 shear	684	680

100m vs 140m HH - 20 years incremental NPV / WTG (k€)

Drivers in key target markets …

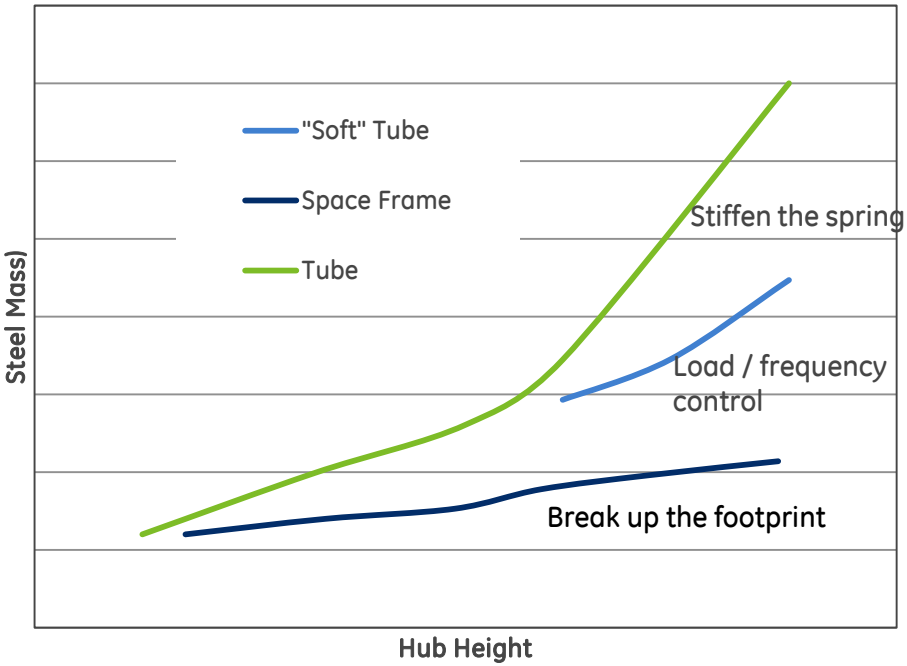
- Thailand… <6 m/s wind & ~20ct/kWh ppa
- Germany… ~6.0 m/s wind & 8 ct/kWh ppa
- Sweden… up to 0.4 shear in forest
- Finland… ~9ct/kWh in forest

Evaluate New Technology in System Eyes

Space Frame Tower

Metal lattice structure … break logistic constraint

Fiberglass coat … Protect from weather



Space Frame Tower Comparison

	Assemble in Factory	Assemble on Site
Direct Material (subject to Local Content Rules)	• Greater mass • "Turnkey" supply chain may shift with project locations	• Lower mass • Global suppliers of multiple subsystems
Logistics (varies by project location)	 • Specialized trailers $30/mile (multiply by tower sections) • Permits/escorts/restrictions	 • Predictable, competitive market • More loads to manage
Installation Cost (varies with labor rates)	 Optimized through 1000's of units	 • Apply factory principles to the field • More people, fixtures?

Challenge: Optimize hub height requires various detailed models

System Optimization of Space Frame Tower

Component Level Analysis

- Reduced *tower mass & cost*
- Removal of *logistic constraints*

Turbine Level Analysis

- Increased *installation* costs
- Reduced *logistic* costs
- *O&M* costs … add cover for weather protection
- Allows *cost-effective scaling* of tower

Fleet Level Analysis

- Economies of scale on *installation* time
- *Market revenues*
- *Market rules*

Value not in 80 to 110m towers, but greater >120m … 3MW products
Most impactful locations have high shear & energy price
Optimized at 139m for 2.75-120 product

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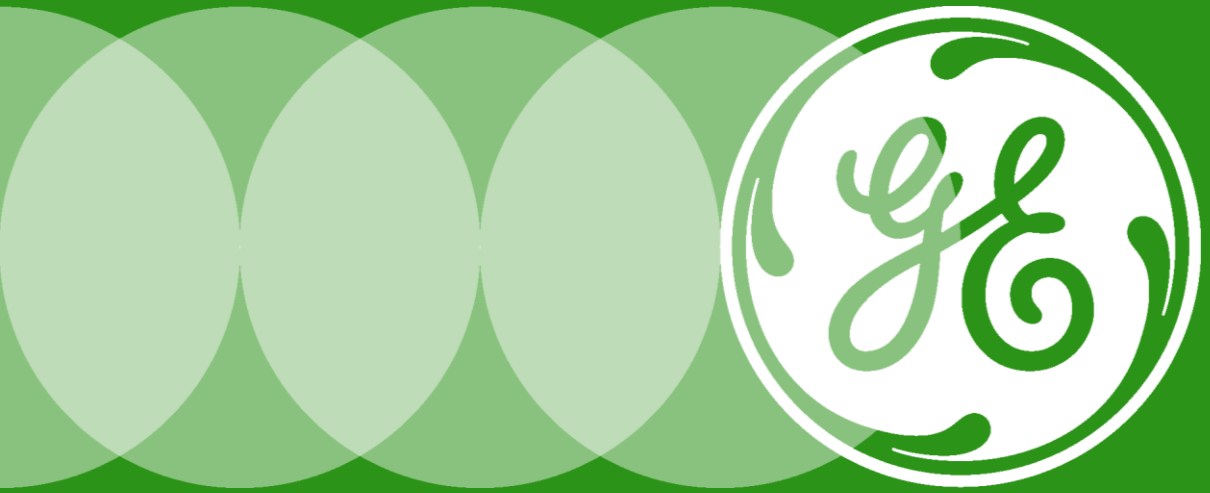

GE Wind Products & Hub Heights

1 & 2 MW Platform

Turbine	Hub Height	Tip Height
1.6-87	80m	123.5
2.75-120	80m 96m (60Hz only)	130 146
1.7-103	80m	131.5
1.85-82.5	65m (50Hz only) 80m	106.25 121.25
1.85-87	80m	123.5
2.3-107	80m	133.5

3 MW Platform

Turbine	Hub Height	Tip Height
2.5-120	85m 110m 120m 139m	145 170 180 199
2.75-120	85m 110m 139m	145 170 199
2.85-100	70m 75m 85m 98.3m	120 125 135 148.3
2.85-103 3.2-103	70m 75m 85m 98.3m	121.5 126.5 136.5 150